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Extended radio emission in BL Lac objects I: the images

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Abstract.
We have observed 28 sources selected from the 1Jy sample of BL Lac objects (Stickel et al. 1991) with the Very Large Array (VLA) in A, B and D configurations at 1.36, 1.66 and 4.85 GHz, and/or with the Westerbork Synthesis Radio Telescope (WSRT) at 1.40 GHz. In this paper we present high sensitivity images at arcsecond resolution of the 18 objects showing extended structure in our images, and of another source from the FIRST (Faint Images of the Radio Sky at Twenty-cm) survey (Becker et al. 1995). In general our high sensitivity images reveal an amount of extended emission larger than previously reported. In some objects the luminosity of the extended structure is comparable with that of FR II radio sources. A future paper will be devoted to the interpretation of these results.

Key words: Galaxies: active — BL Lac objects: general — Radio continuum: galaxies

1. Introduction

A great effort of the recent research on Active Galactic Nuclei (AGN) has been directed to the development of "Unified Schemes": a framework wherein the observational properties of different classes of AGN can be explained as intrinsically similar objects seen at different orientation angles to the line of sight (see Urry & Padovani 1995 and references therein).

In this context, it is now widely accepted that the observed properties of BL Lac objects are largely due to a relativistic jet pointing in the direction of the observer (the Beaming Model; Blandford & Rees 1978), implying the existence of a class of radio sources (hereafter the parent population) intrinsically identical to BL Lacs, but with the jets oriented at large angles with respect to the line of sight.

The nature of the parent population of the BL Lacs has been the subject of several investigations in the past. While some authors confirm that the majority of them are low luminosity edge darkened FR I radio galaxies seen along their radio axis (see Urry & Padovani 1995 and references therein), others suggest that the diffuse radio emission detected around high redshift BL Lacs is more consistent with FR II rather than FR I radio galaxies (see e.g. Kollgaard et al. 1992; Murphy et al.1993).

A straightforward outcome of the beaming model is that all the properties not depending on orientation should be shared by the BL Lac objects and their parent population.

To address this problem we planned to compare the extended radio luminosity of the radio selected 1 Jy BL Lac sample (Stickel et al. 1991) with that of FR I and FR II radio galaxies. In fact, while the morphology is distorted by projection effects, and a morphological classification could be uncertain, the luminosity of the unbeamed emission is suitable for a direct comparison with the extended emission found in the candidate parent population.

Of the 34 BL Lac objects belonging to the 1 Jy sample we have selected the 28 objects without deep radio images at arcsecond scale resolution in the literature, and/or at the arcminute scale. Stickel et al. (1994) added three sources to their original sample: 0218+357, 2029+121 and 2150+173. In particular 0218+357 is a well known gravitational lens (O'Dea et al. 1992; Patnaik et al. 1993, 1995). Since our work started when these three additional sources were not included, and furthermore, in the literature the '1 Jy sample of BL Lac sources' refers to the 34 objects in Stickel et al. (1991), we will not consider the forementioned additional sources.

Here we present data for 28 objects observed with the VLA and/or the WSRT; preliminary results on extended emission and polarization properties for a small fraction of these objects were presented in Stanghellini et al. (1997). In this paper we show the images and briefly discuss the results obtained from our observations. In a forthcoming paper we will give a full discussion of the results. Throughout this paper we use $H_0 = 50$ km s^{-1} Mpc^{-1} and $q_0 = 0.5$.

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2. Observation and data reduction

VLA observations were carried out in 1994 and 1995 at 1.36, 1.66, 4.8 GHz in A, B, and D configurations. WSRT observations took place in Feb. 1994 at 1.4 GHz. In Table 1 we report the journal of these observations.

Table 1. Journal of the observations: col. [1] date of the observations, col. [2] array (A,B,D, for the VLA configurations, W for WSRT), col. [3] observing frequency, col. [4] bandwidth.

date	array	ν(GHz)	$\Delta\nu$(MHz)
18/04/94	A	1.36	50
	A	1.66	25
29/04/94	A	1.36	50
	A	1.66	25
04/07/94	B	1.36	50
	B	1.66	25
	B	4.88	50×2 IFs
22/01/95	D	1.36	50
	D	1.66	25
21/02/95	D	1.36	50
	D	1.66	25
02/94	W	1.40	40

2.1. The VLA data

The VLA data reduction has been performed using the Astronomical Image Processing System (AIPS) developed at the National Radio Astronomy Observatory (NRAO). After a standard calibration we performed several iterations of imaging and phase self-calibration and one final iteration of phase and amplitude self-calibration.

We observed with the VLA in A and B configuration in order to have good sensitivity to radio emitting regions with angular sizes up to 120 arcseconds; the high resolution provided by the A-array data allowed a good measure of the core emission and therefore we managed to have an accurate determination of the extended emission flux density. We also planned to combine the data at 1.36 and 1.66 GHz to improve the uv-coverage and increase the sensitivity, but the latter frequency was generally affected by Radio Frequency Interferences (RFI) and we could not pursue our goal. Short B array observations were carried out at 5 GHz to study and compare the arcsecond scale structure detected in the L band. Finally, a few sources were observed in the D array to search for arcminute scale emission (like in 1807+698).

At 1.36 GHz the images were obtained with a multi-field clean to remove the contribution of strong sources in the field. The r.m.s. noise in the final images is typically in the range 0.07−0.18 mJy/beam, close to the expected thermal noise, with the exception of the sources with declination lower than $-20°$. The dynamic range (peak/noise) is between 1000−9000, with typical values around 5000. The images at 1.66 GHz have been only used to verify the results obtained at 1.36 GHz.

We found it useful to combine L band data taken with different configurations only for a few sources in order to increase the sensitivity to the extended emission while maintaining a good resolution. Given that the flux density of the unresolved core may vary significantly between the epochs of the observations in the A and B configurations, we had to normalize the core flux density before combining the different data sets of the same source.

From the A and B array observations we obtained two subsets, each containing only the visibilities with common uv-coverage. Then we produced an image for each of these subsets and determined the peak flux densities. We subtracted from the original data set with the strongest core a pointlike component with intensity corresponding to the difference between the peak fluxes. Finally we combined the two complete data sets. Only for 1807+698 we also added the data in the D configuration, using the same technique.

2.2. The WSRT data

The WSRT observations were carried out to search for arcminute scale extended emission (like for VLA D-Array data).

The total observing time for the observations at the WSRT was 24 hours. Each source was observed for typically five 15-min snapshots, inclusive of slewing times, in a range of HA in order to obtain an acceptable uv-coverage. The typical resolution was about 13"×13"cos δ and the r.m.s. noise in the image plane was between 0.15 and 0.3 mJy/beam. The data reduction has been done using the NEWSTAR package that allows redundancy self-calibration. The flux density scale has been referred to Baars et al. (1977) by means of the observations of 3C286, whose flux density was assumed to be 14.77 Jy at 1.40 GHz.

The NEWSTAR package allows for the removal of unresolved components (i.e. components with size much smaller than the observing beam) in the imaging process. This has been used to remove the nucleus of each BL Lac object in order to estimate the total flux density of the extended emission.

2.3. Additional images

We also searched for images of the 1 Jy BL Lac sources in the NRAO VLA Sky Survey (NVSS, Condon et al. 1998) and in the FIRST (Becker et al. 1995) survey. Most sources appeared pointlike, except 1514−241 on the NVSS and 0828+493 and 1418+546 on the FIRST. These three images are presented here along with the images obtained from our data, since they show more details than those available in the literature.

3. Results

The VLA and WSRT observations detected extended emission around about 85% of the observed objects; for about 50% of them the flux density of the extended emission we measured is a factor 1.3-3 higher than previously derived from images with lower dynamic range (Antonucci & Ulvestad 1985, Antonucci et al. 1986, Murphy et al. 1993, Kollgaard et al. 1992, Kollgaard et al. 1996). The WSRT and VLA D-array data were effective on the detection of arc-minute scale structures, but only in a few cases we observed significant emission at this scale above a surface brightness of ∼1 mJy/beam.

The images are shown in Fig. 1 through 34 and the image parameters are reported in Table 2. More information on this table is given in the caption. For all the images the contour levels are -3, 3, 6, 12, 25, 50, 100, 200, 400, 800, 1500, 3000 times the image r.m.s..

Table 2. Image parameters. We do not present images for the sources marked with an asterisk because they are unresolved or because the extended structure in our images does not improve the information in the literature. Col. [1] IAU name, col. [2] array (A,B and D, are for the VLA configurations, W is for the WSRT). 'a' and 'b' means that the image is from the FIRST or NVSS, respectively, col. [3] frequency of the observations, col. [4] beam major and minor axes, col. [5] position angle of the restoring beam, col. [6] r.m.s. noise on the image plane, col. [7] peak flux density on the image. When the core has been subtracted, the flux density not restored in the image is shown in parentheses.

[1]	[2]	[3]	[4]	[5]	[6]	[7]
name	array	ν (GHz)	beam (arcsec)	PA (^{o})	r.m.s. (mJy/beam)	peak (mJy/beam)
$0048-097$	A+B	1.36	2.4x1.1	46	0.08	511
	B	4.88	2.2x1.9	-60	0.15	982
$0118-272$	A	1.36	3.0x1.2	-21	0.10	742
	B	4.88	5.3x1.4	36	0.15	663
$0138-097$	A+B	1.36	2.3x1.5	42	0.07	541
	B	4.88	4.3x1.7	-53	0.15	695
$0426-380$	A	1.36	4.4x1.0	23	0.10	624
	B	4.88	5.3x1.4	15	0.15	1371
$0454+844*$	W	1.40	9.2x26.8	57	0.20	1 (310)
$0537-441$	A	1.36	5.3x1.2	1	0.50	3010
	B	4.88	7.1x1.3	-3	1.80	5138
$0716+714*$	W	1.40	17.5x11.0	0	0.30	83 (280)
$0814+425*$	W	1.40	19.5x13.5	22	0.25	10 (1099)
$0820+225*$	W	1.40	33.7x13.8	12	0.30	81 (1988)
$0823+033*$	D	1.36	54.0x43.0	-52	0.15	1479
$0828+493$	B[a]	1.39	5.4x5.4	0	0.13	355
*	W	1.39	18.3x13.1	52	0.3	10 (288)
$0851+202*$	W	1.40	39.4x12.5	3	0.30	2 (1143)
$0954+658$	A	1.36	1.1x1.0	34	0.08	597
	B	4.88	2.8x1.3	49	0.15	523
$1144-379$	A	1.36	3.6x1.1	-9	0.5	21 (1892)
$1147+245$	A+B	1.36	1.3x1.3	0	0.07	796
	B	4.88	2.6x1.9	82	0.10	845
$1308+326$	B	1.46	4.3x4.3	0	0.15	859
$1418+546$	B[a]	1.40	5.4x5.4	0	0.15	566
	W	1.40	17.0x12.0	14	0.25	19 (710)
	D	1.36	68.0x32.0	-69	0.07	815
$1514-241$	A+B	1.36	3.0x2.0	28	0.15	1606
	B	4.88	3.0x1.5	-50	0.17	2918
	D[b]	1.40	45x45	0	0.40	1993
$1519-273*$	A	1.36	3.4x1.4	-30	0.2	1690
*	B	1.36	9.3x3.2	33	0.10	883
$1652+398$	B	1.36	3.5x3.0	-84	0.13	1383
	B	4.88	1.6x1.3	-76	0.18	1320
$1749+701*$	W	1.40	18.3x11.6	-61	0.20	1 (650)
$1803+784$	B	1.36	9.3x4.9	-11	0.07	1761
	B	4.88	2.5x1.2	-13	0.30	2214
$1807+698$	A	1.36	3.2x1.5	-49	0.15	1136
	A+B+D	1.36	7.0x5.5	-22	0.10	1284
	B	4.88	2.5x1.3	-9	0.15	1507
$1823+568*$	W	1.40	30.0x10.0	-53	0.30	50 (1190)
$2007+777$	W	1.40	24.0x10.0	-47	0.25	17 (1095)
$2131-021$	A	1.36	1.6x1.5	1	0.20	1291
	B	4.88	1.9x1.4	-22	0.20	1669
$2240-260$	A	1.36	2.0x1.0	6	0.08	813
	B	4.88	3.7x1.3	-29	0.20	805
$2254+074*$	D	1.36	47.0x42.0	4	0.15	284

The relevant result for our study is the radio luminosity of the extended structure, but we have derived other important physical parameters from the images. The flux density of the extended emission has been determined by subtracting the peak from the total flux density, using the most suitable image, i.e. the image with enough resolution to isolate the core, but still containing all the extended emission. To calculate the luminosity we used the luminosity distance obtained from the redshift. For sources having only a lower limit to the redshift we used this lower value.

Table 3 contains the flux density and luminosity of the extended emission, the largest angular and linear size, the core prominence parameter R and the "sidedness" of the extended emission of the source: 1 if one-sided, 2 if two-sided, P for a pointlike source. The luminosities were K-corrected by the factor $(1+z)^{\alpha_{\rm ext}-1}$, where $\alpha_{\rm ext}$ is the spectral index of the extended structure ($S \propto \nu^{-\alpha}$) and we have used $\alpha_{\rm ext} = 0.8$. In Table 3 we also report the flux densities of the extended emission, as found in the literature, of the remaining 6 sources from the 1 Jy sample and of a few sources also observed by us, whenever the measure found in the literature had a better resolution allowing a more accurate subtraction of the core emission. When necessary, the measures have been scaled to 1.36 GHz.

The largest angular and linear sizes have been calculated only for the sources showing a well defined extended structure. For the one-sided objects we give the largest angular distance from the core.

The core prominence parameter, R, is defined as the ratio between the core and the extended emission flux densities, multiplied by $(1+z)^{-\alpha_{\rm ext}}$, to apply the K-correction, assuming $\alpha_{\rm core} = 0$ for the core spectral index.

In the WSRT images, the cross marks the position of the subtracted core component. For 0454+844, 0814+425, 0820+225, 0851+202, 1749+701, 1823+568, and 2254+074, observed with the WSRT, and 0823+033 (VLA, D configuration) we could not evaluate the contribution of the core and the extended components, due to the relatively low resolution of these arrays; for 0716+714 our measure of the extended emission flux density is lower than that found by Antonucci et al. (1986) due to the low resolution of our data. No image is shown for these sources.

We give now a brief description for each source that showed extended structure and a comparison with previous observations.

0048-097: Figure 1 shows the A+B configuration image. The core emission is located at the center of a diffuse structure and a bright knot (hot-spot?) is seen at the southern edge of the radio source. The 4.88 GHz image (Fig. 2) from the B array does not show all the extended structure seen at lower frequency. The image at 1.46 GHz published by Wardle et al. (1984) only shows the core and a hint of the southern knot. We find a flux density of 176 mJy in the extended emission to be compared to the 95 mJy reported by Antonucci & Ulvestad (1985) based on the image of Wardle et al. (1984). 0048-097 appears only marginally resolved in our D array data.

0118-272: the radio image from the A array (1.36 GHz in Fig. 3) shows a halo around the core that contributes significantly to the total luminosity, while the B configuration image (not shown) displays only a marginally resolved structure. In the image at 4.88 GHz (Fig. 4) there is a hint of a jet extending towards SE. Previous observations of this source are reported by Perley (1982). Our higher dynamic range allows to image the extended emission to larger distances than in Perley (1982); the diffuse emission in our image extends to 18 arcseconds.

0138-097: in the combined A and B array data sets at 1.36 GHz (Fig. 5) we see a weak elongated structure leading to the NW and a rather bright component extending approximately 4" south of the core. The 4.88 GHz image (Fig. 6) does not show clear secondary components, maybe just a clue of the southern one. The source is point-like in the D array image. Previous observations (Perley, 1982) do not reveal any extended structure in this source.

We remark that recent optical observations by Heidt et al. (1996) and Scarpa et al. (1999) show a number of companions within 3 arcseconds from the BL Lac. The extended radio emission in Fig. 5 is aligned with the position of these companions. We cannot rule out that at least part of the extended radio emission we report in Table 3 is associated with any of these structures.

0426-380: this source has a short jet pointing to the NW visible only in the higher resolution images (Fig. 7 and 8). We find a flux density of the extended emission twice the value reported by Perley (1982).

0537-441: the low declination of the source resulted in a very elongated beam in N-S. Nevertheless in our highest resolution image (Fig. 9, A array, 1.36 GHz) 0537-441 shows a curved jet-like structure leading to the west. The radio source is slightly resolved also in the B array image at the same wavelength (not shown). The jet has been also detected at 4.88 GHz, but its surface brightness is lower (Fig. 10). Perley (1982) detects only the knot at the end of the jet.

0828+493: no extended emission has been detected for this source either in our WSRT image or in previous VLA observations (Murphy et al. 1993). However, some extended emission has been recently revealed by the FIRST survey. We used this image (Fig. 11) to derive the numbers in Table 3.

0954+658: Kollgaard et al. (1992) detect a jet extending approximately 5" to the South. Our A array image at 1.36 GHz (Fig. 12) and the 4.88 GHz B array image (Fig. 13) show an elongated structure directed to the SW and then bending to the south. No further extended emission has been detected in our B and D array data at 1.36 GHz.

1144-379: the radio image in the L band is dominated by an unresolved component of 1.9 Jy. Perley (1982) reports an upper limit of 10 mJy for any extended emission. The sources 1144-379 is barely resolved even in the VLA A array images. A coarse estimate of the extended flux, through fitting the radio source with a point-like component and determining the residuals, gives a value of about 20 mJy. In Fig. 14 we show the VLA image in which the arcsecond core has not been restored (its position is marked by a cross). Given the low declination of the source, the uv-coverage is not adequate to allow a proper imaging of this additional component.

1147+245: we detect a diffuse component up to 15" to the

South and another diffuse component located about 10" on the opposite side of the core (Fig. 15), basically in agreement with the image published by Antonucci & Ulvestad (1985). Our measure of the extended emission flux density is about twice their value. In the 4.88 GHz image (Fig. 16) only hints of the extended structures are visible.

1308+326: The VLA data of this source are from a different program, in which 1308+326 was observed as secondary calibrator. This source shows a dominant component which is resolved in the SE direction, a secondary component ∼12" north, and a diffuse halo surrounding the entire structure (Fig. 17). Murphy et al. (1993) resolve the southern diffuse emission in a structure suggesting a helical jet. Our B array image reveals ∼ 30% more flux density in the extended structure than reported by Murphy et al. (1993).

1418+546: Murphy et al. (1993) found a component to the West of the compact core also present in the image from the FIRST survey (Fig. 18). Our WSRT observations (Fig. 19) show that this component is elongated to the south, with an extended flux density higher than reported by Murphy et al. or revealed by the FIRST image. The low resolution D array image (Fig. 20) is dominated by a point-like component; however extended and diffuse emission is detected all around, suggesting the presence of a halo with a total size of 4.5 arcminutes similar to that observed in 1807+698 (see below).

1514-241: Antonucci & Ulvestad (1985) report a component 21" away from the core. Our A+B array image at 1.36 GHz shows a jet emerging along the SE direction and bending towards NE after a dozen of arcseconds, for a total extent $\sim 55''$ (Fig. 21), also visible in the 4.88 GHz image (Fig. 22). The image from the D array (Fig. 23) was obtained from the NVSS survey (Condon et al. 1998), and clearly shows a diffuse emission on the arcmin scale on the same side of the jet. The flux density of this component was added to the estimate from our A+B array image.

1519-273: this is a very compact source, unresolved in our images at the resolution of 1". The source is still unresolved at the mas scale (O'Dea et al. 1991, Shen et al. 1997). Perley (1982) gives an upper limit of about 5 mJy for any extended emission. We did not detect significant extended emission above 0.5 mJy/beam, and we do not show any image for this source.

1652+398: Kollgaard et al. (1992) find a diffuse emission at 5 GHz which is in agreement with the 75" wide halo we detect in our higher resolution B array image at 1.36 GHz (Fig. 24). Our 4.88 image shows instead only a small fraction of the extended emission visible in the L band.

1803+784: Kollgaard et al. (1992) find a weak component 45" away from the core, while Antonucci et al. (1986) detect a diffuse emission around the core. In our image (Fig. 26) a jet-like structure is present connecting the secondary component to the core, and additional diffuse emission on the west side. The 4.88 GHz image (not reported) shows only an unresolved core.

1807+698: Kollgaard et al. (1996) find the radio structure of this source, at arcsecond resolution, consisting of a ∼30" long jet extending from the core to the west direction. Wrobel & Lind (1990) find a double lobed structure of total extension of $\sim 60''$, at 4.88 GHz (VLA, B configuration). Our image from A+B+D configuration (Fig. 27) shows a diffuse halo of ∼220" of extension surrounding the core-jet structure in agreement with the morphology seen by Wrobel & Lind (1990). The jet is clearly visible in our A array image at 1.36 GHz (Fig. 28) and in the B array 4.88 GHz image (Fig. 29).

2007+777: the WSRT image has not enough resolution to characterize the extended structure, which is better highlighted by the VLA observations of Murphy et al. (1993). However the total flux density of the extended emission in our WSRT image exceeds the measure from Murphy et al. by about 30% (Fig. 30).

2131-021: the unresolved core is located at the NW edge of the radio emission (Fig. 31). Two jet like structures are oriented in P.A. $\sim -90°$ and P.A. $\sim -170°$; all this is reminiscent of NAT/WAT morphology. The B array image at 1.36 GHz does not reveal any further extended emission and we can therefore consider that the total angular size of the extended radio emission is about 9". Observations of this source were made by Perley (1982) and he found an extended flux of about 50 mJy. Recently a VLA image in B configuration at 1.49 GHz was published by Hutchings et al. (1998). The lower resolution of their observations did not allow to properly separate the core flux density from the tail-shaped extended emission yielding to underestimate the total extended flux density.

2240-260: in this object the unresolved core sits in the center of a diffuse extended emission which can be characterized by two misaligned and bent jet-like structures (Fig. 33). The total size of the extended emission is about 26" corresponding to 212 kpc at the redshift of the host galaxy. No previous arcsecond scale observations have been found in the literature.

Fig. 1. 0048-097, VLA A+B configuration, 1.36 GHz. The restoring beam is 2.4x1.1 arcsec in PA 46°. The peak flux density is 511 mJy/beam and the r.m.s. noise on the image is 0.08 mJy/beam

Fig. 2. 0048-097, VLA B configuration, 4.88 GHz. The restoring beam is 2.2x1.9 arcsec in PA -60°. The peak flux density is 982 mJy/beam and the r.m.s. noise on the image is 0.15 mJy/beam

Fig. 3. 0118-272, VLA A configuration, 1.36 GHz. The restoring beam is 3.0x1.2 arcsec in PA -21°. The peak flux density is 742 mJy/beam and the r.m.s. noise on the image is 0.10 mJy/beam

Fig. 4. 0118-272, VLA B configuration, 4.88 GHz. The restoring beam is 5.3x1.4 arcsec in PA 36°. The peak flux density is 663 mJy/beam and the r.m.s. noise on the image is 0.15 mJy/beam

Fig. 5. 0138-097, VLA A+B configuration, 1.36 GHz. The restoring beam is 2.3x1.5 arcsec in PA 42°. The peak flux density is 541 mJy/beam and the r.m.s. noise on the image is 0.07 mJy/beam

Fig. 6. 0138-097, VLA B configuration, 4.88 GHz. The restoring beam is 4.3x1.7 arcsec in PA -53°. The peak flux density is 695 mJy/beam and the r.m.s. noise on the image is 0.15 mJy/beam

Fig. 7. 0426-380, VLA A configuration, 1.36 GHz. The restoring beam is 4.4x1.0 arcsec in PA 23°. The peak flux density is 624 mJy/beam and the r.m.s. noise on the image is 0.10 mJy/beam

Fig. 8. 0426-380, VLA B configuration, 4.88 GHz. The restoring beam is 5.3x1.4 arcsec in PA 15°. The peak flux density is 1371 mJy/beam and the r.m.s. noise on the image is 0.15 mJy/beam

Fig. 9. 0537-441, VLA A configuration, 1.36 GHz. The restoring beam is 5.3x1.2 arcsec in PA 1°. The peak flux density is 3010 mJy/beam and the r.m.s. noise on the image is 0.50 mJy/beam

Fig. 10. 0537-441, VLA B configuration, 4.88 GHz. The restoring beam is 7.1x1.3 arcsec in PA -3°. The peak flux density is 5138 mJy/beam and the r.m.s. noise on the image is 1.80 mJy/beam

Fig. 11. 0828+493, VLA B configuration, 1.40 GHz (from FIRST, Becker et al. 1995). The restoring beam is 5.4x5.4 arcsec. The peak flux density is 355 mJy/beam and the r.m.s. noise on the image is 0.13 mJy/beam

Fig. 12. 0954+658, VLA A configuration, 1.36 GHz. The restoring beam is 1.1x1.0 arcsec in PA 34°. The peak flux density is 597 mJy/beam and the r.m.s. noise on the image is 0.08 mJy/beam

Fig. 13. 0954+658, VLA B configuration, 4.88 GHz. The restoring beam is 2.8x1.3 arcsec in PA 49°. The peak flux density is 523 mJy/beam and the r.m.s. noise on the image is 0.15 mJy/beam

Fig. 14. 1144-379, VLA A configuration, 1.36 GHz. The restoring beam is 3.6x1.1 arcsec in PA -9°. The peak flux density is 21 mJy/beam and the r.m.s. noise on the image is 0.5 mJy/beam

Fig. 15. 1147+245, VLA A+B configuration, 1.36 GHz. The restoring beam is 1.3x1.3 arcsec. The peak flux density is 796 mJy/beam and the r.m.s. noise on the image is 0.07 mJy/beam

Fig. 16. 1147+245, VLA B configuration, 4.88 GHz. The restoring beam is 2.6x1.9 arcsec in PA 82°. The peak flux density is 845 mJy/beam and the r.m.s. noise on the image is 0.10 mJy/beam

Fig. 17. 1308+326, VLA B configuration, 1.46 GHz. The restoring beam is 4.3x4.3 arcsec. The peak flux density is 859 mJy/beam and the r.m.s. noise on the image is 0.15 mJy/beam

Fig. 18. 1418+546, VLA B configuration, 1.40 GHz (from FIRST, Becker et al. 1995). The restoring beam is 5.4x5.4 arcsec. The peak flux density is 566 mJy/beam and the r.m.s. noise on the image is 0.15 mJy/beam

Fig. 19. 1418+546, WSRT, 1.40 GHz. The restoring beam is 17.0x12.0 arcsec in PA 14°. The peak flux density is 19 mJy/beam and the r.m.s. noise on the image is 0.25 mJy/beam

Fig. 20. 1418+546, VLA D configuration, 1.36 GHz. The restoring beam is 68.0x32.0 arcsec in PA -69°. The peak flux density is 815 mJy/beam and the r.m.s. noise on the image is 0.07 mJy/beam

Fig. 21. 1514-241, VLA A+B configuration, 1.36 GHz. The restoring beam is 3.0x2.0 arcsec in PA 28°. The peak flux density is 1625 mJy/beam and the r.m.s. noise on the image is 0.15 mJy/beam

Fig. 22. 1514-241, VLA B configuration, 4.88 GHz. The restoring beam is 3.0x1.5 arcsec in PA -50°. The peak flux density is 2918 mJy/beam and the r.m.s. noise on the image is 0.17 mJy/beam

Fig. 23. 1514-241, VLA D configuration, 1.40 GHz (from NVSS, Condon et al. 1998). The restoring beam is 45.0x45.0 arcsec. The peak flux density is 1993 mJy/beam and the r.m.s. noise on the image is 0.40 mJy/beam

Fig. 24. 1652+398, VLA B configuration, 1.36 GHz. The restoring beam is 3.5x3.0 arcsec in PA -84°. The peak flux density is 1383 mJy/beam and the r.m.s. noise on the image is 0.13 mJy/beam

Fig. 25. 1652+398, VLA B configuration, 4.88 GHz. The restoring beam is 1.6x1.3 arcsec in PA -76°. The peak flux density is 1320 mJy/beam and the r.m.s. noise on the image is 0.18 mJy/beam

Fig. 26. 1803+784, VLA B configuration, 1.36 GHz. The restoring beam is 9.3x4.9 arcsec in PA -11°. The peak flux density is 1761 mJy/beam and the r.m.s. noise on the image is 0.07 mJy/beam

Fig. 28. 1807+698, VLA A configuration, 1.36 GHz. The restoring beam is 3.2x1.5 arcsec in PA -49°. The peak flux density is 1136 mJy/beam and the r.m.s. noise on the image is 0.15 mJy/beam

Fig. 29. 1807+698, VLA B configuration, 4.88 GHz. The restoring beam is 2.5x1.3 arcsec in PA -9°. The peak flux density is 1507 mJy/beam and the r.m.s. noise on the image is 0.15 mJy/beam

Fig. 30. 2007+777, WSRT, 1.40 GHz. The restoring beam is 24.0x10.0 arcsec in PA -47°. The peak flux density is 17 mJy/beam and the r.m.s. noise on the image is 0.25 mJy/beam

Fig. 31. 2131-021, VLA A configuration, 1.36 GHz. The restoring beam is 1.6x1.5 arcsec in PA 1°. The peak flux density is 1291 mJy/beam and the r.m.s. noise on the image is 0.20 mJy/beam

Fig. 32. 2131-021, VLA B configuration, 4.88 GHz. The restoring beam is 1.9x1.4 arcsec in PA -22°. The peak flux density is 982 mJy/beam and the r.m.s. noise on the image is 0.20 mJy/beam

Fig. 33. 2240-260, VLA A configuration, 1.36 GHz. The restoring beam is 2.0x1.0 arcsec in PA 6°. The peak flux density is 813 mJy/beam and the r.m.s. noise on the image is 0.08 mJy/beam

Fig. 34. 2240-260, VLA B configuration, 4.88 GHz. The restoring beam is 3.7x1.3 arcsec in PA -29°. The peak flux density is 805 mJy/beam and the r.m.s. noise on the image is 0.20 mJy/beam

Fig. 27. 1807+698, VLA A+B+D configuration, 1.36 GHz. The restoring beam is 7.0x5.5 arcsec in PA -22°. The peak flux density is 1284 mJy/beam and the r.m.s. noise on the image is 0.10 mJy/beam

Table 3. Observational data of the whole 1Jy sample. The question marks in columns [2] through [7] indicate indicate a very uncertain value. Column [1] IAU name; [2] red shift: Stickel et al. (1993) for all sources but 0138-097 and 0454+844 (Stocke & Rector 1997), 0814+425 (Falomo et al. 1997) and 2131-021 (Drinkwater et al. 1997); [3] extended flux, where necessary scaled to 1.36 GHz; [4] Log of extended luminosity; [5] maximum diameter of the source in arcsec and [6] in kpc; [7] ratio core/extended flux density; [8] sidedness: '1' one-sided extended emission, '2' double-sided extended emission, 'P' unresolved or barely resolved source; [9] references for the information given in this table: 1 this paper, 2 Murphy et al. (1993), 3 Antonucci et al. (1996), 4 Antonucci & Ulvestad (1995), 5 Kollgaard et al. (1992), 6 Perlman & Stocke (1994), 7 FIRST survey.

[1]	[2]	[3]	[4]	[5]	[6]	[7]	[8]	[9]
Name	z	S_{ext} (mJy)	Log L_{ext} (W Hz^{-1})	LAS (arcsec)	Size (kpc)	R	S	Ref.
0048−097	>0.2	176	>25.50	24	>101	<2.5	1	1
0118−272	>0.557	168	>26.40	18	>133	<3.0	1	1
0138−097	0.733	50	26.13	23	186	6.8	2	1
0235+164	0.940	36	26.21	13	110	18.2	1	2
0426−380	>1.030	86	>26.67	6	>51	<4.1	1	1
0454+844	>1.34	...	...	...	...	...	...	...
0537−441	0.896	220	26.95	13	109	8.2	1	1
0716+714	>0.2	387	>25.85	18	>76	<0.87	1	3
0735+178	>0.424	24	>25.31	10	>66	<70.0	1	2
0814+425	>0.6	76	>26.12	6	>46	16.8	1	2
0820+225	0.951	700	27.51	12	101	1.3	1	2
0823+033	0.506?	5	24.79?	18	129?	191.0	1	2
0828+493	0.548?	25	25.56?	42	331?	10.0	2	7
0851+202	0.306	17	24.87	28	156	81.6	1	6
0954+658	0.367	34	25.33	6	37	14.7	1	1
1144−379	1.048	10?	25.75?	1?	8?	106.5?	P	1
1147+245	>0.2	50	>24.96	34	>144	<13.7	2	1
1308+326	0.997	105	26.73	31	264	4.7	1	1
1418+546	0.152	47	24.69	75	259	13.5	1	1
1514−241	0.049	210	24.34	270	354	7.4	1	1
1519−273	>0.2	...	...	...	...	...	P	1
1538+149	0.605	234	26.62	7	53	4.5	1	2
1652+398	0.033	95	23.65	75	68	14.2	2	1
1749+096	0.320	...	...	...	...	...	...	...
1749+701	0.770	12	25.55	3	24	32.2	?	5
1803+784	0.684	43	26.00	56	444	27.0	1	1
1807+698	0.051	1010	25.06	222	302	1.2	2	1
1823+568	0.664	525	27.06	25	196	1.3	?	2
2005−489	0.071	...	...	...	...	...	...	...
2007+777	0.342	41	25.35	28[a]	166[a]	21.1	2[a]	1
2131−021	1.285	182	27.20	9	77	3.7	1	1
2200+420	0.069	40	23.92	15	27	78.4	1	4
2240−260	0.774	333	26.99	26	212	1.6	2	1
2254+074	0.190	17	24.44	18	73	23.2	1	4

Note
a. Value calculated from the image of Murphy et al. (1993)

4. Discussion and conclusions

Unified Schemes Models consider the low-power FR I radio galaxies as the parent, unbeamed population of BL Lac objects. The boundary between FR I and the powerful FR II radio galaxies has been found to lie around 2×10^{25} W Hz^{-1} at 178 MHz (Fanaroff & Riley 1974). At higher frequencies, like at 1.36 GHz, the segregation in radio power is not as evident as at 178 MHz, and in the literature one commonly finds that $\sim10^{24.5}$ W Hz^{-1} is considered the borderline. Indeed, it is well known (e.g. Bridle 1984; 1987) that this boundary at 1.4 GHz is not really sharp, although one can infer that *most* of the FR I radio galaxies are below that limit, while *most* of the FR II lie above. We therefore investigated the properties of the extended emission in the 1 Jy BL Lac sample, and in particular we studied the extended, unbeamed emission.

The monochromatic luminosities derived from our observations are often larger than those found in the literature; furthermore, for a few sources we have revealed extended structure previously unknown. Therefore this work is more complete and goes deeper than previous efforts in this direction.

In Fig. 35 we present a plot of the distribution of the luminosity of the extended, unbeamed emission for the 1 Jy BL Lac sample, as given in Table 3, once the arcsecond scale core has been subtracted out. We have used the measurements derived from our observations, completed with data taken from the literature (see Table 3). On this respect, we chose the better suited images/measurements in order to have about the same accuracy in the subtraction of the arcsecond core emission.

Fig. 35. Numeric distribution of the radio luminosity of the extended emission at 1.36 GHz for the 1 Jy sample, as from Table 3. The symbol ">" is a lower limit to the luminosity, as derived from the minimum redshift. When the radio luminosity could not be determined with enough accuracy (0823+033, 0828+493 and 1144-379, see text), we used the symbol "?" to remark the uncertain estimate.

The unbeamed radio luminosities at 1.36 GHz clearly extend beyond the limit (not really sharp at this frequency) of $10^{24.5}$ W Hz^{-1} separating FR I from FR II radio galaxies, with just a few objects with radio luminosities typical of the brightest FR II galaxies. In general the luminosity distribution of the whole sample seems rather smooth and covers a wide range of radio luminosities.

In a forthcoming paper we will discuss in detail our results, and we will compare the radio properties of the Radio Selected BL Lacs (i.e. the 1 Jy sample) with those of X-ray Selected BL Lacs (i.e. EMSS sample) and further with those of FR I and FR II radio galaxies.

5. Summary

We have presented interferometric radio data at 1.36, 1.66 and 4.8 GHz with the VLA at A, B and D configurations, and at 1.4 GHz with the WSRT, on 28 of 34 objects of the 1 Jy sample of BL Lac objects (Stickel et al. 1991). We have obtained high sensitivity radio images at the arcsec resolution, in order to evaluate the extended luminosity of these objects, most of which had poor or no radio data at this resolution. We found that most of the sources observed possess substantial extended emission, and often our flux densities exceed those previously reported into the literature. A few sources have unbeamed radio luminosities at 1.36 GHz of the order of 10^{27} W Hz^{-1}, supporting the hypothesis that the parent population of BL Lac objects is a mixture of FR I and FR II radio sources.

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